Constraining symmetry energy with Heavy Ion Collisions

Outline:
1. Symmetry energy and neutron stars
2. Experimental signatures from HI collisions
   a) Isotope distributions
   b) Isospin diffusion
   c) n/p ratios
3. Summary & connection to neutron star
4. HiRA at MSU

IWM05, Catania, Italy
Nov 28-Dec 1, 2005
Symmetry Energy in Nuclei

\[ B = a_v A - a_s A^{2/3} + \delta - a_c \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \frac{(A-2Z)^2}{A} \]

\[ (a_v^{sym} A - a_s^{sym} A^{2/3}) \frac{(A-2Z)^2}{A^2} \]

Inclusion of surface terms in symmetry
Size & Structure of Neutron Star depends on EOS

- Dense neutron matter.
- Strong mag. field.
- Strange composition → pasta and anti-pasta phases; kaon/pion condensed core …

**EOS influence**

✓ R,M relationship
✓ maximum mass.

Free Fermi gas EOS:

mass < 0.7 M
✓ cooling rate.
✓ core structure
Heavy ion collisions:
Access to high density nuclear matter

\[ E/A (\rho, \delta) = E/A (\rho,0) + \delta^2 \cdot S(\rho) \quad \delta = (\rho_n - \rho_p) / (\rho_n + \rho_p) = (N-Z)/A \approx 1 \]

Results from Au+Au flow (E/A~1-8 GeV) measurements include constraints in momentum dependence of the mean field and NN cross-sections.
Extrapolation to neutron stars

\[ E/A (\rho, \delta) = E/A (\rho,0) + \delta^2 \cdot S(\rho) \]

\[ \delta = (\rho_n - \rho_p) / (\rho_n + \rho_p) = (N-Z)/A \approx 1 \]

- The asymmetry term contributes a greater uncertainty than does the symmetric matter matter EOS.

Heavy ion collisions:
Access to low density nuclear matter
E/A < 100 MeV; Multifragmentation Scenario

-- Initial compression and energy deposition
-- Expansion – emission of light particles.
-- Cooling – formation of fragments
-- Disassembly

Model Approaches
Dynamical and Statistical
Isotope Distribution Experiment

*MSU, IUCF, WU collaboration*

Sn+Sn collisions involving $^{124}\text{Sn}$, $^{112}\text{Sn}$ at E/A=50 MeV

*Miniball + Miniwall*
*4 $\pi$ multiplicity array*
*Z identification, A<4*

*LASSA*
*Si strip +CsI array*
*Good E, position, isotope resolutions*

*Xu et al, PRL, 85, 716 (2000)*
Measured Isotopic yields

Central collisions

Multifragmentation

R_{21}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)}
Isoscaling: \[ R_{21} = \frac{Y_2(N,Z)}{Y_1(N,Z)} \propto e^{\alpha N + \beta Z} \]

Observed in many reactions by many groups.

\[ R_{21}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)} \approx C \cdot e^{N\Delta \mu_n / T + Z\Delta \mu_p / T} \]

### Isoscaling in experimental data and models

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Isotopes</th>
<th>Energy</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{124}\text{Sn} + ^{124}\text{Sn} / ^{112}\text{Sn} + ^{112}\text{Sn}$</td>
<td>50</td>
<td><strong>PRL, 86, 5023 (2001)</strong></td>
<td></td>
</tr>
<tr>
<td>$^{112}\text{Sn} + ^{58}\text{Ni} / ^{124}\text{Sn} + ^{64}\text{Ni}$</td>
<td>35</td>
<td>NPA732 (2004) 173</td>
<td></td>
</tr>
<tr>
<td>$p, \text{He}+(^{124}\text{Sn} / ^{112}\text{Sn})$</td>
<td>660-1530</td>
<td><strong>PRC 65(2002)044610</strong></td>
<td></td>
</tr>
<tr>
<td>$^{58}\text{Ni} + ^{58}\text{Ni} / ^{58}\text{Fe} + ^{58}\text{Fe}$</td>
<td>30,40,47</td>
<td>PRC 68,021602(2003)</td>
<td></td>
</tr>
<tr>
<td>$^4\text{He} + ^{124}\text{Sn} / ^4\text{He} + ^{112}\text{Sn}$</td>
<td>50</td>
<td>PRC 47, 1553 (1993)</td>
<td></td>
</tr>
<tr>
<td>$^{16}\text{O} + ^{232}\text{Th} / ^{16}\text{O} + ^{196}\text{Au}$</td>
<td>8.6</td>
<td>PR 44, 93 (1978)</td>
<td></td>
</tr>
<tr>
<td>$^{86}\text{Kr} + ^{124}\text{Sn} / ^{86}\text{Kr} + ^{116}\text{Sn}$</td>
<td>35</td>
<td>PRC 68, 024605 (2003)</td>
<td></td>
</tr>
<tr>
<td>$^{28}\text{Si} + ^{124}\text{Sn} / ^{28}\text{Si} + ^{112}\text{Sn}$</td>
<td>30,50</td>
<td>PRC 69, 031602 (2004)</td>
<td></td>
</tr>
<tr>
<td>$^{12}\text{C} + ^{124}\text{Sn} / ^{12}\text{C} + ^{112}\text{Sn}$</td>
<td>300, 600</td>
<td><strong>PRL (2005)</strong></td>
<td></td>
</tr>
<tr>
<td>Spallation reactions</td>
<td>1 GeV</td>
<td>nucl-ex/0112014</td>
<td></td>
</tr>
<tr>
<td>n induced fissions</td>
<td>14 MeV</td>
<td><strong>PRC 69,044607</strong></td>
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</tbody>
</table>

### Models

**Statistical models:**
- SMM (GC, C, μC), MMC, statistical decays,
- EES, LGM, QSM

**Dynamical models:**
- AMD, QMD

**Others:**
- MD, fission,
- fragmentation (AA),
- percolation

**Isoscaling everywhere??**
Effects of sequential decays on isoscaling

\[ \alpha = \frac{4C_{\text{sym}}}{T} \left( \frac{Z_1}{A_1} - \frac{Z_2}{A_2} \right) \]

- Statistical models
  - Effects are small (<20%)
- Dynamical models
  - Effects are large ~ 50%

![Graph](image-url)
AMD simulations with sequential decays

Light particles have much lower symmetry energy.

Isoscaling persists after decay but sensitivity to interactions disappears.
Isospin Diffusion--Isospin Transport Ratio

Isospin diffusion occurs only in asymmetric systems $A+B$

No isospin diffusion between symmetric systems

Non-isospin diffusion effects

$\rightarrow$ same for $A$ in $A+B$ & $A+A$; same for $B$ in $B+A$ & $B+B$

$$R_i = \frac{2x_{AB} - x_{AA} - x_{BB}}{x_{AA} - x_{BB}}$$

Rami et al., PRL, 84, 1120 (2000)

$$x_{AB} = \text{experimental or theoretical isospin observable for system } AB$$

$\rightarrow R_i = 1.$

$\rightarrow R_i = -1.$

Non-isospin transport effects are “cancelled”??
Emission patterns of charged particles e.g. $^7$Li

Observable: $V_{//}$ vs. $V_{\perp}$

Acceptance: No detector coverage around beam & detector energy thresholds

Emission from projectile and target residues would create ridges from Coulomb repulsions.
Emission patterns of $^7$Li & $^7$Be from $^{124}$Sn+$^{112}$Sn; E/A=50 MeV

$Y(^7Li)$ enhanced from $^{124}$Sn

$Y(^7Be)$ enhanced from $^{112}$Sn
Isospin transport observable

\[ \frac{Y(^7\text{Li})}{Y(^7\text{Be})} \]

Mainly dominated by Coulomb

\[ V_{\parallel}(\text{au}) \]

\[ 1^{12}\text{Sn} + 1^{24}\text{Sn} \]

\[ ^7\text{Li} \]

\[ ^7\text{Be} \]

\[ ^7\text{Li} \text{ enhanced from } 1^{24}\text{Sn} \]

\[ ^7\text{Be} \text{ enhanced from } 1^{12}\text{Sn} \]

Ratio \( \frac{Y(^7\text{Li})}{Y(^7\text{Be})} \)

Mainly dominated by Coulomb

How to observe isospin transport?

\[ R_i = \frac{2x_{AB} - x_{AA} - x_{BB}}{x_{AA} - x_{BB}} \]
Coulomb & other (preequilibrium & sequential) effects are “cancelled”

\[
R_i = \frac{2x_{AB} - x_{AA} - x_{BB}}{x_{AA} - x_{BB}}
\]

Rami et al., PRL, 84, 1120 (2000)
Rapidity dependence in isospin diffusion

For $y > 0.7y_{\text{beam}}$ measurements are consistent with isospin transport ratios obtained from isoscaling.

Tsang et al., PRL 92, 062701(2004)
Diffusion occurs within \( \approx 120 \) fm/c. More mixing with soft \( E_{\text{sym}}(\rho) \)
consistent with large \( E_{\text{sym}} \) at \( \rho < \rho_0 \).
Less mixing with stiff \( S(\rho) \).

\( \gamma \approx 1.1 \)
\( \gamma \approx 0.6 \)
Constraints on symmetry term in EOS from isospin diffusion

\[ E(\rho, \delta) = E(\rho, 0) + E_{\text{sym}}(\rho)\delta^2; \quad \delta = (\rho_n - \rho_p) / (\rho_n + \rho_p) \]

Assume \( E_{\text{sym}}(\rho) \propto (\rho / \rho_0) ^\gamma \)

**BUU+m*: Transport theory based on Boltzmann Equations
+ include momentum dependence in mean field.
+ in medium \( \sigma_{nn} \)

\( ^{112,124}\text{Sn} + ^{112,124}\text{Sn} \)
E/A=50 MeV
Peripheral collisions
**Heavy Ion Collisions:**

Central collisions (isospin fractionation)

- n/p ratios; \( <E_n>, <E_p> \)
- probes the pressure from asymmetry term at saturation density and below.

The symmetry term affects the emission of n and p.

\[ \frac{n}{p}(\text{stiff } \gamma \sim 1.1) < \frac{n}{p}(\text{soft } \gamma \sim 0.6) \]

Observables in HI collisions

Assume \( E_{\text{sym}}(\rho) = C_{\text{cym}}(\rho / \rho_0)^\gamma \)
n/p Experiment $^{124}\text{Sn} + ^{124}\text{Sn}; ^{112}\text{Sn} + ^{112}\text{Sn}; E/A=50\text{ MeV}$
N-detection – neutron wall
p-detection: Scattering Chamber

WU MicroBall (b determination)

3 particle telescopes (p, d, t, $^3$He, …)

Impact parameter: $b < 0.2$

Central

# of charged particles

$^{124}$Sn + $^{124}$Sn

Famiano et al
n/p Double Ratios (central collisions)

Double Ratio \[
\frac{{}^{124}\text{Sn} + {}^{124}\text{Sn}; Y(n)/Y(p)}}{{}^{112}\text{Sn} + {}^{112}\text{Sn}; Y(n)/Y(p)}
\]

minimize systematic errors

There will be improvements in both data (analysis) and BUU (1997) calculations.

Clusters can be addressed within coalescence invariant analyses

Data, Famiano et al, preliminary

BUU: Li, Ko, & Ren PRL 78, 1644, (1997)

Famiano et al
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Experimentalists: HiRA collaboration
Michigan State University
Washington University
L.G. Sobotka, R.J. Charity
Indiana University
R. deSouza, V. E. Viola
The High Resolution Array

• Flexible easily reconfigured array with 20 independent telescope (can be expanded).
• High resistivity silicon; $\Delta E \approx 35$ keV FWHM, per signal.
4x CsI(Tl) 4cm

Si-ΔE 65 μm

32 strips v (front)

32 strips h. (back)

32 strips (front, 2mm pitch)

Beam
deSouza, IU
HiRA Electronics (WU+SIU)

ASIC: Application Specific Integrated Circuit

32 Channel ASIC board

16 Slot Motherboard.
HiRA Electronics Setup Behind Detectors in Vacuum Chamber
The S800 Spectrograph
Expt 02023: Summation of 8 telescopes after gain-matched. 
(32x8 strips & 4x8 CsI)
HiRA Experiments

- **July-August: Experiment #02023**
  - $S_p$ measurement for a rp-process endpoint nucleus
    \[ ^{71}\text{Br} + ^{9}\text{Be} \rightarrow ^{69}\text{Br}^* \rightarrow ^{68}\text{Se} + p \] (HiRA+S800+MCP)

- **Oct 2-10: Experiment #02019**
  - Resonance Spectroscopy
    \[ ^{12}\text{Be} \rightarrow ^{6}\text{He} + ^{6}\text{He} \] (HiRA+LASSA)

- **Oct 19-30: Experiment #02018**
  - rp-Process mass measurements
    \[ ^{66}\text{Ge} + p \rightarrow d + ^{65}\text{Ge} \] (HiRA+S800+MCP)

- **Jan/Feb, 2006: Experiment #05023**
  - Spectroscopic factors in p-shell nuclei (HiRA+S800)

- **Summer, 2006:**
  - Correlation experiment
  - HiRA+4pi
Collaboration

MSU / NSCL
- W.G. Lynch
- M.B. Tsang
- F. Delaunay
- M. Wallace
- M.-J. van Goethem
- A. Rogers
- M. Mocko
- Jenny Lee

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- R.T. de Souza
- A.L. Caraley
- B.P. Davin
- S. Hudan

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- L. Sobotka
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